Temporal and spatial variations in freeze warnings in the conterminous United States: 2005–2018

Brandon Lawhorn^{1,2} · Robert C. Balling Jr¹

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Abstract

It is well-documented that the United States (US), along with other mid-latitude land locations, has experienced warming in recent decades in response to changes in atmospheric composition. Among other changes, Easterling (2002) reported that the frost-free period is now longer across much of the US with the first frost in fall occurring later and the last freeze in spring occurring earlier. In this investigation, we explore spatial and temporal variations in all freeze warnings issued by the US National Weather Service. Freeze warning counts are highest in the southeastern US peaking overall in the spring and fall months. Freeze warnings tend to occur more toward summer moving northward and westward into more northerly states. Consistent with the warming in recent decades, we find statistically significant northward movements in freeze warning centroids in some months (December, February) across the study period (2005–2018). Detection of spatial and temporal trends in freeze warnings may be of interest to any number of scientists with applied climatological interests.

1 Introduction

Knowing when and where freezing temperatures may occur is important for those in the agriculture and horticulture communities, among many others. In the United States, the US National Weather Service (NWS) for over the past decade has been providing forecast warnings of potential freezing temperatures, with a majority of these warnings occurring during early spring and late fall for most of the country. As these warnings are dependent upon temperature, there is potential to use these warnings as an alternative way to detect the effects of trends in near-surface air temperatures.

Stocker et al. (2013) and others have reviewed extensive literature and concluded that the global mean near-surface air temperatures, based on multiple independently derived datasets, have increased by approximately 0.85 °C over the past 130 years, with

most of that warming occurring in recent decades. Stocker et al. (2013) also note that it is very likely that the number of cold days and nights has decreased in the most recent period. More specifically, Rowe and Derry (2012) concluded that during the period 1961–2010, the number of record low daily minimum temperatures has been significantly and steadily decreasing across all areas in the US. Grundstein and Dowd (2011) examined records from across the US from 1949 to 2010 and found that many stations experienced a positive trend in extreme minimum apparent temperatures. As minimum temperatures have increased, the diurnal temperature range continues to decrease across most of the conterminous US (Qu et al. 2014).

Given our focus on freezes and freeze warnings, a paper by Easterling (2002) is of importance to our interests. He gathered daily maximum and minimum temperature records from approximately 1000 cooperative stations throughout the US from 1948 to 1999. He then analyzed the number of days below freezing, the dates of the first autumn freeze and the last springtime freeze, and the length of the frost-free season. In general, he found that in the western US, the date of the first fall freeze was trending to later, the date of the last spring freeze was occurring earlier, and the frost-free length was increasing; all trends in the west were highly statistically significant. The southeastern US had cooled slightly and no significant trends in frost dates were identified. Given the rather obvious high correlation between freeze observations and freeze warnings, we anticipate finding patterns consistent with Easterling (2002) as we explore freeze warning data.

✉ Brandon Lawhorn
belaw17@gmail.com

Robert C. Balling, Jr
robert.balling@asu.edu

¹ School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ 85287, USA

² Present address: National Weather Service, Pendleton, OR 97801-4593, USA

Fig. 1 **a** Aggregate of freeze warnings (without hard freeze warnings). **b** Hard freeze warnings. **c** All freeze-related warnings (freeze and hard freeze) over the 2005–2018 period

The purpose of our study is to develop and present a basic climatology of freeze warnings in the United States including an attempt to identify potential trends in freeze dates and frost-

Fig. 2 **a** Average last spring freeze-related warning date. **b** Average first fall freeze-related warning date. **c** Average difference in days between average last spring warning date and average first fall warning date

free periods. Using the freeze warning data issued by the NWS, we examine spatial and temporal trends in these data that may be apparent given the trends in minimum temperatures reported by others for the conterminous US.

2 Freeze warning dataset

In this study, the primary dataset consists of freeze warning data issued by Weather Forecasting Offices (WFO) under the NWS. The data consist of freeze warnings issued between 2005 to the end of 2018 as well as hard freeze warnings issued from 2007 to the end of 2018 across the contiguous US. Each warning issued by a specific WFO is defined by the time that freezing temperatures are expected to occur, as well as the region, or regions that will be impacted. One might anticipate a bias to issue freeze warnings in areas where sensitive crops (e.g., citrus or fruit) are a significant part of local agriculture. A forecaster bias may also exist to issue warnings to err on the side of caution in areas where below freezing temperatures are uncommon.

Freeze and hard freeze “watches” were available in the original dataset; however, freeze “warnings” preclude with greater certainty that temperatures at or below freezing will occur. Defined by the NWS, a WFO provides freeze and hard freeze warnings in conjunction with the beginning and ending of local growing seasons (NWS 2018). WFOs can still provide these warnings outside of these time periods in special circumstances. In order for a freeze warning to be issued, forecasted low temperatures are expected to be at 32 °F (0 °C) or between 32 °F (0 °C) and 28 °F (−2.2 °C). When the lowest temperatures are forecasted to be below 28 °F (−2.2 °C), a hard freeze warning is then issued for the affected regions.

The archived freeze and hard freeze warning datasets were obtained from the Iowa State University of Science and Technology (<https://mesonet.agron.iastate.edu>). The freeze warnings dataset archive is updated at the end of each day, starting from when the freeze and hard freeze warnings were first implemented in 2005 and 2007, respectively. The database consists of several different file formats containing the warning data; we utilized datasets in this research stored in the shapefile format which is compatible with Geographic Information Systems (GIS). Esri’s ArcGIS program, ArcMap 10.5 (<http://desktop.arcgis.com/en/arcmap/>), was chosen for its ability to read the shapefile format as well as its ability to perform spatial statistics on the datasets. In each shapefile, the warnings, as well

Fig. 3 Freeze and hard freeze warnings by month

Fig. 4 **a** The total number of warnings issued from March to June through the study period. **b** The total number of warnings issued from September to December through the study period

as their relevant non-geographic information, are represented by a set of polygons with boundaries defined by the region(s) for which the forecast is issued. The final dataset used for analysis in this paper contained both the freeze and hard freeze warnings. The unique warning type code designated at the time of warning was also used in order to identify these warnings during analysis.

In order to properly analyze the freeze and hard freeze warning dataset, a better, more consistent geographical representation was needed. To account for the differing extents of each region for which a warning was issued, as well as any changes made to warning boundaries through the study period, a grid made up of 0.25° latitude by 0.25° longitude cells was laid across the contiguous US. For each freeze and hard freeze warning issued during the study period, a cell and/or group of cells contained within the warning zone were assigned the attributes of the warning. Through this process, spatial and temporal information regarding freezing and hard freeze warnings could be analyzed. In regard to the temporal analysis, duplicate warnings for each cell were removed before the analysis.

Fig. 5 Spatial distribution monthly maxima occurrence of all freeze warnings (freeze plus hard freeze)

Fig. 6 Mean centroid of all freeze warnings by month, 2005–2018

Fig. 7 Freeze and hard freeze warnings by year

3 Freeze warning climatology

During the study period, over 124,000 freeze-related warnings were issued by the NWS. Of these warnings, the freeze warnings (as opposed to hard freeze) were an overwhelming majority with just over 109,000 being issued. Figure 1 a shows the spatial distribution of these freeze warnings from 2005 to 2018. Evident in the figure, the maxima of freeze warnings are mostly located from the Gulf States into the Ohio River basin region. Other notable regions are the West Coast and Great Plains of the US. Hard freeze warnings issued by the NWS make up approximately 15,000 of the freezing temperature warnings. In Fig. 1b, hard freeze warnings issued between 2007 and 2018 are presented. The figure shows that hard freeze warnings are mostly confined to the Gulf States and have a lesser spatial extent compared with just freeze warnings. However, the aggregate of freeze and hard freeze warnings (Fig. 1c) is similar to the pattern in Fig. 1a; the map pattern correlation between the two is 0.952 and is statistically significant at the < 0.01 level of confidence.

Through the study period, the average last spring (Jan–June), average first fall (July–Dec), and average difference between the last spring and first fall warnings were calculated. For the study area, the average last spring warning date was

found to be around April 17th; the average last fall warning date was found to be October 20th; and the average difference in days between the last spring warning and the first fall warning was 187 days. Figure 2 a shows the spatial distribution of the average last spring warning from 2005 to 2018. The figure shows a gradual retreat north of the average last spring warning in the eastern half of the US as well as the West Coast, whereas the more mountainous region of the US generally receives the last spring warning from April to mid-June. In Fig. 2b, the spatial distribution of average first fall warning is presented. The figure shows a similar pattern to the spring warnings, where a wave of first fall warnings is observed advancing toward the southern US from the north. This pattern is also evident in the more mountainous terrain of the western US. Figure 2 c also shows the average difference between the last spring warning and the first fall warning. As evident in the figure, the further north a region is located generally correlates with a lesser period of time between last spring warnings and first fall warnings.

As noted previously, many WFOs in the NWS provide freeze warnings during the beginning and ending of growing seasons. An analysis of the temporal aspect of the freeze and hard freeze warnings dataset reflect this practice in the NWS. Evident in the bimodal pattern seen in Fig. 3, the maxima of aggregate warnings occur during October through November as well as March through April. Obviously, the greatest occurrence of freezing temperatures occurs during December through February; however, the NWS does not deem it necessary to issue freeze warnings throughout most of the country where below-freezing temperatures are common. Though a large occurrence of warnings do occur during these months, these warnings during fall and spring are mostly confined to regions in the central and eastern US (Fig. 4). Examining the spatial distribution of maximum warning count by month (Fig. 5) also reveals that a large percentage of the US receives the freezing temperature warnings during these months. When looking only at freeze warning pattern in Fig. 3 (as opposed to

Table 1 South-north movement of freeze and hard freeze warnings (italic with asterisks indicate significance at the < 0.05 level of confidence)

Month	Slope (freezes)	Significance (freezes)	Slope (hard freezes)	Significance (hard freezes)	Slope (all freezes)	Significance (all freezes)
September	0.03	0.72	0.07	0.83	0.03	0.72
October	0.13	0.20	0.13	0.40	0.12	0.21
November	0.04	0.41	0.19	0.24	0.05	0.38
December	0.15	0.10	<i>0.33*</i>	<i>0.04*</i>	<i>0.19*</i>	<i>0.03*</i>
January	−0.04	0.79	0.06	0.57	0.01	0.96
February	<i>0.45*</i>	<i>0.03*</i>	<i>0.36*</i>	<i>0.05*</i>	<i>0.46*</i>	<i>0.01*</i>
March	0.18	0.34	0.16	0.71	0.18	0.32
April	−0.09	0.54	0.05	0.84	−0.08	0.55
May	0.04	0.76	−0.07	0.66	0.03	0.23
June	0.05	0.78			0.05	0.78

hard freeze warnings), it is evident that these warnings drive the bimodal pattern observed in the aggregate of the warnings.

An additional method of exploring the spatial dimension of freeze warnings involves calculating the mean centroid of warnings by month. This basically involves determining the mean latitude and mean longitude of freeze warnings within a given month (means for all January events, February events, and so on). As seen in Fig. 6, the warnings in the coldest months (November to March) have their centroids in the southerly locations, while the centroids in the warmer months appear to migrate northerly and westerly.

4 Temporal trends of freeze warnings

Figure 7 presents the freezing temperature warnings by year and highlights aggregate warning maxima in 2007, 2010, and 2012 as well as minima in 2005, 2006, and 2015. The relatively low values in 2005 and 2006 may be related to the phasing in of the freeze warnings by the WFO's. As with the spatial characteristics of the warnings, the freeze warnings have a greater influence over the aggregate of the warnings. However, 2010 did experience a higher than average amount of hard freeze warnings, which contributed to the maxima during that year.

Trend analysis was conducted over the dataset by year by determining the total number of freeze warnings within each year. Given the relatively short time period (2005–2018) and therefore small N-size, our results did not identify a statistically significant trend. We repeated the analysis using monthly data thereby expanding the N-size, but the results were still not statistically significant. Conducting the analysis for each individual month did not identify significant trends in any month. Along with testing for trends in the number of warnings, we determined the average date of the last spring warning for each cell in each year. Averaging those dates for each year produced a time series of average dates; once again, no significant trend was identified given the small N-size. We repeated the analysis for the average date of first fall freeze warnings and found no significant trends. Not surprisingly, no significant trend was found for the average length of time between the warnings.

Finally, for each month from September to June, we calculated the latitudinal trends in the location of the spatial centroid of freeze warnings over the 2005–2018 time period. This was done by first finding the mean centroid of each warning category (freeze, hard freeze, and aggregate warnings) for each month over each year during the study period. We used simple regression analysis to determine if significant latitudinal trends could be detected over the study period. As seen in Table 1, 25 of the 29 trend values were positive indicating a northward migration in freeze warnings. Despite a relatively small N-size, five of the trends were found to be statistically significant at the <0.05 level of confidence. Across all warning categories, February warnings were observed to be

moving northward through the study period. For hard freeze warnings and all freeze-related warnings, the month of December is also observed to have a significant northward migration.

5 Conclusions

Along with revealing spatial dimensions of the basic climatology of freeze warnings issued by WFO's over the period 2005–2018, we found evidence of a significant northward migration of the warnings in some months of the year. Our results add a spatial dimension to the findings of Easterling (2002) who showed fall freezes were beginning later, spring freezes ending earlier, with the resulting frost-free length increasing over much of the country. Our results were also consistent with the general warming observed in the United States over recent decades, particularly given the warming to be more pronounced in minimum as opposed to maximum daily temperatures.

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